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FAST RESPONSE METERS FOR PULSED LIQUID FLOW.(U)

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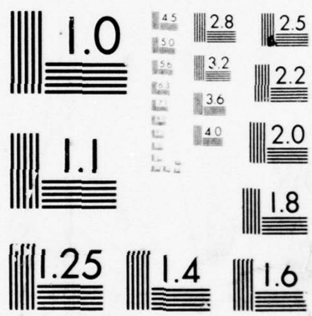

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FAST RESPONSE METERS FOR PULSED LIQUID FLOW

by

P.G. Herrington

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Farnborough, Hants

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A brief summary is given of five other techniques, which were investigated but which exhibit limited performance for this particular application.

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A brief summary is given of five other techniques, which were investigated but which exhibit limited performance for this particular application.

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1 INTRODUCTION

An electrothermal hydrazine thruster (EHT) may be used for the attitude control of a satellite by generating a series of small impulses from decomposed hydrazine. Hydrazine is fed via an electromagnetic flow control valve and injector tube to a resistively heated decomposition chamber where it is thermally decomposed. The hot gases produced are exhausted through a nozzle to produce thrust. For fine accuracy of attitude control small impulses of thrust may be produced by rapid switching of the valve; on times as low as 50 ms are not uncommon. In order to assess the efficiency of the thruster operating in this mode it is necessary to measure accurately both the impulse produced and the corresponding quantity of fuel used. This requires a relatively fast response fluid meter to measure the pulsed hydrazine flow.

Four relevant specifications for the operation of an acceptable fluid meter are:-

(i) Compatibility with the corrosive properties of hydrazine and safety from the hazardous effects of personal contact.

(ii) A mean flow rate of 100 mg/s.

(iii) A hydrazine supply pressure of up to 2200 kN/m^2.

(iv) Capable of responding closely to pulse durations of the order of 50 ms.

There are many techniques used for measuring liquid flow but they seldom combine both fast response and resolution. For example the small flow rate in this application excluded the use of electromagnetic induction or ultrasonic techniques both of which exhibit reasonable response. Conversely very sensitive techniques such as the laser Doppler anemometer, hot wire anemometer and self heated thermistor were found to be impractical. The laser Doppler anemometer and thermistor exhibited limited flow response and the hot wire anemometer had hydrazine adaptability problems.

Two methods developed to measure the quantity of fuel used per thruster pulse are described in this Report. The techniques employed were on orifice type flowmeter and an instrument which measured the vertical displacement of a flexible reservoir subsequently called a Liquid Expulsion Meter (LEM). The experimental results obtained using de-ionised water as a representative substitute for hydrazine are described.

There has been no opportunity, as yet, to test either of the flowmeters in an EHT test rig with hydrazine. Although the flowmeters were originally

designed for EHTs the two techniques may have applications for future thruster development and for the measurement of other small fluid expulsions.

In addition five other techniques investigated are briefly summarised.

2 THE ORIFICE FLOWMETER

2.1 Principle of operation

A well established method of measuring flow is the orifice flowmeter but commercially available instruments tend to cater for flow rates much larger than 100 mg/s. An experimental orifice meter was therefore constructed to assess the feasibility of using such a device with an EHT.

An orifice flowmeter consists essentially of an orifice plate placed perpendicular to the direction of fluid movement, with pressure tappings either side of the plate to monitor the resulting pressure drop (see Fig 3). The relationship between the pressure drop and volumetric flow is derived from[1] (see Fig 1):

(a) Bernoulli's principle for an incompressible fluid flowing steadily and horizontally

$$\frac{P_1}{\omega} + \frac{V_1^2}{2g} = \frac{P_2}{\omega} + \frac{V_2^2}{2g} \tag{1}$$

(b) the continuity equation

$$Q = A_1V_1 = A_2V_2 = \text{volumetric flow rate.} \tag{2}$$

These two expressions when combined give

$$Q \triangleq C_d \frac{d^2\pi}{4}\sqrt{\frac{2g(P_1 - P_2)}{\omega}} \tag{3}$$

where C_d is the discharge coefficient normally found experimentally,

ω is the specific weight (density × g),

d is the diameter of the orifice,

g is the gravitational constant,

$P_1 - P_2$ is the pressure drop across the orifice due to the fluid flow. 092

Ideally the flowmeter should be placed as close to the decomposition chamber as possible. However, the volume downstream of the flow control valve must be kept small to reduce thruster decay times. Hence the flowmeter can only be placed

upstream of the valve. A consequence of this is that if any gases or vapour accumulate in the volume between the meter and injector tube they will reduce the ability of the orifice meter to respond accurately to the flow through the injector. The following hypothetical example illustrates this effect (see Fig 1). The steady supply pressure P_1 is 410 kN/m^2 with 21 kN/m^2 dropped across the orifice meter for a flow of 100 mg/s.

For an initial gas volume V of 126 mm^3 the relative flows through the orifice and injector tube, dm_1/dt and dm_2/dt respectively, are illustrated in Fig 2 (see Appendix A) for a valve on time of 12 ms. This figure shows that the area under the injector flow curve between T_1 and zero equals the total area under the orifice flow curve. The orifice meter is therefore accurately measuring the fuel mass expelled per pulse regardless of its response to flow through the injector tube under these idealised conditions. With pulsing flows the fluid acceleration through the orifice is inconstant. In addition other departures from the ideal include momentary flow oscillations due to the valve's sharp action and viscosity changes of the fluid to be measured. The main purpose of the experimental flowmeter was to establish the importance of these or any other effects in measuring the fuel expelled per pulse.

2.2 Experimental orifice flowmeter

A schematic diagram of the meter and ancillary experimental apparatus is shown in Fig 3. The dismantled orifice plate housing is shown in Fig 4 with the orifice plate and two nickel sealing discs. Knife edges in the two housing blocks ensured a good seal between the orifice plate and the housings. The orifice plate was a stainless steel disc with a 0.18mm hole drilled in the centre. Around the hole on the downstream side the plate was undercut to reduce the hole length to as small as practical.

Two perpendicular holes were drilled one in each stainless steel housing block, either side of the orifice plate, to mate with an SE Labs.74, (345 kN/m^2) differential pressure transducer. These pressure transmission holes were placed symmetrically about the orifice to give equal response to signals from any transient pressure reversals. A 10 micron filter was placed immediately upstream of the orifice meter assembly, to minimise the risk of
092 partially blocking the orifice. The orifice meter outlet was connected to an electromagnetic fluid control valve and the flow was regulated by a hypodermic tube 25 mm long and 0.15 mm internal diameter attached to the valve outlet.

De-ionised water was used as a substitute for hydrazine since it has very similar physical properties. Nitrogen was used to pressurise the water supply.

Fig 5 shows the prototype orifice flowmeter assembly with its transducer signal conditioning and power supply electronics. The electronics housing has the cover removed. There were two by-pass valves connected around the orifice housing, one manual the other electromagnetic. These valves were used for priming and evacuating the system, the electromagnetic valve giving remote control for subsequent use in a vacuum chamber.

2.3 Pressure transducer electronics

A schematic diagram of the associated transducer electronics is shown in Fig 6 with a detailed circuit diagram in Fig 7. This circuitry was arranged in a tier of three boards. The top board (seen in Fig 5) was an oscillator-amplifier-demodulator unit. This energised the SE74 pressure transducer, being a variable reluctance half-bridge type, and tailored to a bandwidth of 550 Hz.

The output of the top board being proportional to the pressure drop across the orifice, was fed to the central, square rooting circuitry board, to produce the desired linear flow versus voltage output (see section 2.1). Because of the high fluid supply pressure the SE74 transducer presented a significant common mode pressure signal to the square rooting circuitry in addition to the desired differential pressure measurement. This common mode signal could be automatically zeroed with a dc restorer during the EHT pulse interval or manually backed off for steady flow measurements. In practice, with an EHT, there are momentary reverse pressure levels across the orifice due to the action of the flow control valve, these producing corresponding negative voltage inputs to the square rooting circuitry. The integrated circuits used for evaluating the square root are naturally only sensitive to positive inputs and so these negative signals were fed via an inverter to a second square root module. These two signal paths were then combined by a subtractor to reproduce the original square rooted differential pressure signal in its correct phase.

The bottom circuit board was an incremental integrator[2] connected to the output of the square rooting circuitry. This unit computed the total fluid mass passing through the orifice. In addition it served to calibrate the orifice meter and to check that it was functioning correctly by comparing its total signal output with the total mass of expelled liquid.

2.4 Steady flow calibration

The system was initially evacuated using a rotary pump and then primed with the by-pass valve open.

To calibrate the orifice meter the forward flow was varied by altering the fluid supply pressure between 69 kN/m^2 and 965kN/m^2 in five steps. At each pressure step the flow was turned on for approximately 60 s, the exact time being measured by an electronic counter. The common mode pressure signal was zeroed at each step either manually or automatically (see section 2.3). The mass of liquid expelled per step was measured to within 5 mg and the mean flow evaluated. Simultaneously the output of the incremental integrator was monitored by an ultra-violet oscillograph and again the mean voltage was evaluated. This method of determining the voltage output overcame the problems of estimating the mean level of small pressure drifts that occurred during the 60 s for which the test was made. It also averaged transient signals caused by the initiation of flow and breakdown of liquid surface tension at the 10 micron filter paper. A straight line through the minimal scatter in the mean flow versus mean voltage points was evaluated. This gave the steady flow relationship of the form

$$V = a \frac{dm}{dt} + b \; . \tag{7}$$

By reversing the orifice meter inlet-outlet connections the reverse steady flow calibration was obtained. This time the mean voltage was determined using a digital multi-meter as the integrator only catered for transient reverse flow signals. As the expected total reverse flow would be a small percentage of the overall flow profile for the EHT this less rigorous approach was justified. The calibration obtained for the prototype orifice meter is shown in Fig 8. All static fluid signals were reduced to zero by either the dc restorer or manual back off. The reason for the appearance of the constant b , which is more apparent on the reverse flow calibration (0.4893 V), is probably due to the effects of hysteresis associated with the pressure transducer's sensing diaphragm. The value 0.4893 V represents only 0.2% of the transducer's full range output.

2.5 Pulsing flow operation

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For pulsing flows the flow control valve and the dc restorer were controlled and synchronised by a pulse generator. The outputs of the square rooter,

integrator and fluid control valve were monitored by the UV oscillograph for several tens of pulses. The total mass of the expelled liquid was resolved to within 5 mg using the chemical balance. Typical pulse signals are shown in Fig 9. The pulse integrals were invariably nearly identical for a train at constant supply pressure but for thoroughness each pulse area was individually evaluated. The total volt second product from the integrator trace was read off and equated to the straight line calibration.

$$\int_0^T V\,dt = am + bT , \tag{8}$$

therefore

$$m = \frac{1}{a}\left\{\int_0^T V\,dt - bT\right\} . \tag{9}$$

The total value of m for all the pulses was then compared to the total mass of expelled liquid and the degree of agreement was a measure of the accuracy of the flowmeter response to pulse flow. As an example, for 52 100 ms pulses as shown in the lower half of Fig 9 the mass of expelled water was 390 mg. According to the orifice meter the mass was 396 mg. Accuracies within ±2% were easily achieved for pulse widths down to 50 ms (0.45 s intervals) for similar total amounts of fluids. The oscillations on the flow profile were caused by the fluid resonating with the gas trapped in the system. These were initially excited by the sharp action of the fluid control valve, both the frequency and initial amplitude increasing with supply pressure.

During the early development of the orifice meter trouble was experienced with the orifice continually and steadily blocking. The cause was finally traced to a reaction between a brass Simplifix fitting and the stainless steel filter housing. A white residue was being formed which collected around the orifice. Because the area of the orifice will be only approximately 0.025 mm^2 for this type of meter scrupulous cleanliness and attention to the pipe system should be observed to prevent partial blocking.

A typical degradation in a flow signal due to partial blocking of the orifice is shown in the top half of Fig 9. The slower response could be partly due to more gas in the system but the higher steady state level was due to the orifice condition.

2.6 Effects of viscosity on the calibration

To obtain an idea of the effects of viscosity on the calibration of the orifice flowmeter a mixture of 50% Isopropyl alcohol (IPA) and de-ionised water was used. The calibration is shown in Fig 10 compared to one obtained with only de-ionised water. [These were obtained at the beginning of the flowmeter development programme using a commercially manufactured oscillator-demodulator system, which subsequently proved to be slightly inefficient due to an internal fault developing in an encapsulated unit. The results may therefore be more indicative than absolute.] The density of the IPA plus water mixture was 0.9 that of water tending to increase the flow for the same pressure drop across the orifice (see equation (3)). But the viscosity was about 1.9 times that of de-ionised water making the discharge coefficient C_d less for the same pressure differential. It would therefore be essential to calibrate the orifice meter with the fluid to be measured unless the fluids are sufficiently similar.

3 LIQUID EXPULSION METER (LEM)

3.1 Principle of operation

The LEM is a device for transferring small amounts of liquid from a comparatively large pressurized reservoir and simultaneously producing a fast response voltage signal proportional to the expelled fluid volume.

A sectional view of the LEM is shown in Fig 11. It is merely a series device in the hydrazine supply system. Either fluid-feed pipe is connected to the main reservoir through an electromagnetic control valve (valve 1) with the other pipe connected via another control valve (valve 2) to the thruster, see Fig 15. A metal bellows forms a tee junction with these pipes and hence acts as a secondary miniature reservoir. Around the bellows is placed a pressure chamber maintained at the same pressure as the main fluid reservoir. Initially with valve 1 open and valve 2 shut the differential pressure across the bellows is zero. When valve 1 is shut the bellows is compressed by the force of the supply pressure in the pressure chamber, expelling its internal liquid mass through valve 2. If valve 2 is now shut and valve 1 opened the differential pressure created by the compression of the bellows causes fluid to be drawn back into the bellows from the main reservoir. The bellows has a linear internal volume versus displacement relationship. A displacement transducer mounted in the pressure chamber top senses the bellows' movement thus producing a measure of the liquid being expelled by the bellows. To maintain an uninterrupted flow through the device valve 2 need not necessarily be inhibited while the bellows is filling.

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3.2 Prototype mechanical construction (see Fig 11)

The LEM was made entirely of stainless steel for hydrazine compatibility, except the bellows. The bellows was specially designed and manufactured for the purpose and was made of electro-deposited nickel of 0.03 mm wall thickness with a spring rate of approximately 18 N/cm. The total continuous permissible vertical movement of the bellows was 1.22 mm giving a working internal volume displacement of 50 mm^3. A dismantled view of the LEM is shown in Fig 12. The bellows was electron beam welded to both its anchor plate and the end disc, the latter forming the electrical capacitance plate associated with the displacement transducer. Because the displacement sensor formed part of the pressure chamber top a specially modified sensor was made to withstand the maximum fluid supply pressure of 2200 kN/m^2. This prevented the Araldite insulation, between the guard ring (which can just be seen on the left of Fig 12) and outer sleeve, taking the full shear stress otherwise imposed by the supply pressure. Positioning of the displacement sensor was by means of the transducer adjustment and locking nuts using the associated electronics to measure vertical movement. It was set 0.05 mm above the bellows and disc with the bellows relaxed. The assembled LEM is shown in Fig 13, the fluid pipes at the bottom and the nitrogen supply pipe to the pressure chamber at the front.

3.3 Electronic signal conditioning and control

The displacement transducer electronics is shown in Fig 14. The unit was mains energised and consisted of a 16kHz oscillator, high gain and input impedance ac tuned amplifier and an amplitude demodulator unit. The oscillator was connected to the amplifier input through a 'purpose built' 1p capacitor with a PTFE dielectric for environmental stability. The displacement transducer, whose effective capacitance range was approximately 3p down to 0.3p, formed the feedback loop of the amplifier thus producing a sine wave output whose amplitude was proportional to displacement. Because of the extremely small signal capacitances involved the amplifier was housed in a separate partitioned screening box, to reduce stray signal paths. As the bellows end disc was connected to the amplifier output this would ground the output via the test site thruster rig. A separate floating supply was therefore required to energise the oscillator and amplifier. The demodulator was a conventional precision full wave rectifier followed by a low pass filter with a bandwidth of 230 Hz.

A separate fluid valve control system for the LEM was required. The circuit diagram is shown in Fig 14. Starting with the bellows filled, valve 1 shut and valve 2 being pulsed by the clock pulse input from an external source, the operation was as follows. Integrated circuits 10, 11, 9 and 1 averaged the amount of fluid being expelled per pulse, multiplied this by a gain or safety factor, and compared this to the amount of expendable fluid left in the bellows. When the latter became insufficient for another pulse, valve 1 was opened to replenish the bellows, valve 2 being inhibited. As previously mentioned, valve 2 need not necessarily be stopped at this time. IC16 sensed when the bellows was filled and closed valve 1. In the event of the control circuitry permitting another pulse with insufficient reserves in the bellows the averaging circuitry was overridden and valve 1 opened. To prevent the sequence starting again during a clock pulse ICs 12 and 13 ensured the system was inhibited until the commencement of the next full clock pulse duration.

Fig 13 shows the transducer electronics on the right with the top cover removed and the control electronics on the left. The zero offset control on the transducer electronics enabled valve 1 to be turned off while the bellows was still under slight compression giving faster refilling. The meter on the control electronics gave an instant visual display of the bellows movement.

3.4 Main sources of error

Because the bellows had stiffness any vertical displacement was accompanied by a reduction in the internal pressure of the fluid. Gas present in the downstream system would inevitably expand causing an error in the relationship between the bellows and liquid volume displacements. This small error depends partly on the amount of gas trapped in the system which can be determined by measuring the bellows movement for an increase in pressure when both valves 1 and 2 are closed. A correction factor can then be readily applied to the V/mg calibration as shown in Appendix B.

Another source of error was the temperature coefficient of sensitivity of the transducer electronics V/mm. An increase in temperature from 24°C to 39°C gave an average 0.12%/°C variation.

The third error source was the change in the dielectric constant of the
092 supply pressure nitrogen with variation in pressure. This, as with air, is virtually a linear relationship[3] and gives an increase of approximately 1% at 2200 kN/m^2 at 20°C. The effective capacitance between the transducer and

bellows end disc therefore increases with supply pressure and gives a corresponding inverse reduction in the sensitivity of the LEM.

3.5 Calibration of LEM

A schematic diagram of the calibration set up is shown in Fig 15. Initially the system was evacuated with a rotary pump. Valve 1 was then opened for priming of the system with de-ionised water at ambient pressure. The nitrogen supply pressure was gradually applied to both the main reservoir and LEM pressure chamber to a level of 965 kN/m^2.

For a full compression of the bellows a nominal voltage output between 0.5 V to 10 V was produced. To expose any non-linearities over this range the amount of fluid expelled between zero volts and four nominal levels of 2 V, 4 V, 7 V and 9 V was resolved. Because of the small volume displacement ($\hat{=}$ 12.6 mm^3) of the bellows for a single compression corresponding to approximately 2 V a more practical approach giving a larger mass of fluid, expelled under working conditions, was adopted. This entailed pulsing the LEM continuously with 50 ms pulses every second while temporarily feeding an external voltage to IC1 of the control circuitry to restrict the total bellows displacement to the desired nominal level. The pulses were stopped when approximately 700 mg of water had been expelled, a comparatively easier mass to resolve.

The total vertical displacement of the bellows corresponded to the sum of the individual pulse voltage signal levels. The voltage output of the displacement transducer together with the valves 1 and 2 current signals were monitored on a UV recorder. Fig 16 shows a tracing of a typical sequence of pulses in a train each expelling approximately 6 mg. The four ranges produced a sensitivity of 0.1767 V/mg with a maximum error of ±0.7%. Because of the residual gas volume (35 mm^3) trapped in the system the ideal calibration was evaluated as 3.3% higher (see Appendix B) *ie* 0.1825 V/mg. Subsequent use of the LEM would require the new gas volume and supply pressure to be taken into account for slight modification to this basic sensitivity, if finer accuracy was desired. Another check calibration at 2420 kN/m^2 was carried out. After taking into account the above mentioned and the increased dielectric constant of the transducer the ideal sensitivity was evaluated as 0.1819 V/mg. This was only 0.33% down, the LEM exhibiting basic insensitivity to supply pressure.

4 OTHER FLOWMETERING TECHNIQUES INVESTIGATED WITH LIMITED PERFORMANCE

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There are numerous techniques used to measure both liquid levels and flow but they rarely combine both fast response, fine resolution and practical

adaptability for measuring corrosive and hazardous liquids such as hydrazine. Before the development of the two potentially successful instruments previously described several tentative methods were tried. The particularly demanding specification associated with EHT development proved them all inadequate either in response or resolution. A brief description of these methods is given as some may have applications in their own right or provide a starting point for other engineers.

4.1 Capacitance level sensor

A sectional view of the capacitance level sensor (CLS) is shown in Fig 18. The comparatively low electrical impedance fluid in the reservoir formed the outer conducting plate of a cylindrical capacitor. The dielectric was made of PTFE both for compatibility with hydrazine and to produce a contact angle greater than 90°, preventing wetting as the liquid moved down the reservoir. A centre electrode of stainless steel formed the inner capacitance plate. Electrical contact to the fluid in the reservoir was through the stainless steel outer body. The total volume of the reservoir was approximately 5 cc and its geometry produced an electrical capacitance of 18 p when full.

The electrical capacitance C was proportional to the height of the fluid and the level sensor was energised from a low impedance sine wave source $V \sin \omega t$ such that the current through the capacitance was measured (*ie* $|i| = V\omega c$) to give an output proportional to the liquid level.

This method exhibited inadequate resolution for pulsing flows of 50 ms duration, owing to interaction between the liquid and PTFE caused by surface tension. An examination, with a travelling microscope, of the moving liquid level showed its reluctance to flow smoothly and uniformly over the dielectric surface. The output voltage signal produced as the liquid flowed steadily from the CLS was differentiated and is shown in a tracing of a UV oscillograph recording in Fig 17. This shows quite markedly the surface tension effect making the measurement of 50 ms pulses impractical. In an attempt to improve the CLS polythene was tried as an alternative dielectric and an octagonal cross section as opposed to cylindrical. Similar results were obtained.

4.2 Inductive piston level sensor (IPLS)

A schematic diagram of the IPLS is shown in Fig 20. Fluid control
092 valves 1 and 4 were operated together and similarly valves 2 and 3. With valves 1 and 4 on, as shown in the diagram, the PTFE piston moved to the right through the centre of a precision bore glass tube of 5 mm internal diameter.

Eight electromagnetic induction coils were placed in sequence around the glass tube. As the piston moved through a coil its inductance was increased by the ferrite core embedded in the PTFE piston. The coil was suitably damped and energised by a current ramp to produce a flat topped voltage waveform. The amplitude of the waveform was measured, this being proportional to the inductance, which in turn indicated very precisely the position of the piston with minimal effects from stray capacitances and coil resistance. As the piston approached the end of the coil the voltage signal reached an upper trip level. This automatically switched the excitation signal to the next coil along the tube via a series of relay contacts. The output calibration signal is shown in Fig 19, (obtained by pushing the piston through with a micrometer depth gauge). When the piston had moved through the last coil to the upper trip point valves 1 and 4 were switched off and valves 2 and 3 on. This moved the piston back through the tube to the left this time the lower trip points sequentially switching the coil excitation volts. This arrangement of fluid control valves was to enable a more continuous flow through the system from a comparatively large reservoir, hence reducing the need for refilling. A reversible counter controlled the relays and indicated which coil the piston was traversing through.

Even though the system was evacuated with a rotary pump prior to priming with de-ionised water, there was always some residual gas in the system. The piston had by necessity to be a tight fit to effect a leak proof seal with the glass tube. The combination of the gas and piston friction produced poor response to pulsing flows, the piston taking several seconds to reach equilibrium. Several pistons were made with varying areas of contact and fit but the system still proved to be impractical for fast response movements.

4.3 Thermistor flowmeter

Using thermistors to measure flow is a well known technique. The thermistor is operated in its self-heating mode and placed in the flow stream. The thermal conductivity of the flow medium varies with flow producing a tendency to change the thermistor resistance. They are extremely sensitive, the Fenwal Thermistor Manual claiming that flow rates of 0.001 cc/min can be measured.

To obtain minimal thermal lag when measuring varying flows a recognised technique is to operate the thermistor in a constant temperature mode. This was achieved by placing a Fenwal GB38P12 fast response glass probe thermistor in one arm of a bridge circuit, the bridge unbalance being sensed as the flow was

pulsed. A fast acting high gain negative loop altered the bridge supply to reproduce balance. The bridge supply volts was monitored on a UV oscillograph. The thermistor was placed through a hole in the wall of a glass tube and protruded into the flow stream. The relative increase in response when operated in the constant temperature mode as opposed to constant current can be seen in Fig 21, for nitrogen flowing through the tube, the thermistor temperature being $65^{o}C$.

To measure the response to pulsing liquid flow water was passed through the tube at 110 mg/s steady flow and then turned on and off by a fast action tap. The sluggish response is shown in Fig 22.

Hot-wire anemometers have much faster responses but because of their basic fragility, and difficult adaptability for use with hydrazine (which is thermally unstable) no experiments using them as a substitute for thermistors were carried out.

4.4 Laser Doppler anemometer

A Laser Doppler anemometer is a very sophisticated instrument capable of measuring the velocity of flow at finite points without any impedance to the flow. The system senses the Doppler frequency shift of scattered light from small particles in the flow stream traversing through the point of measurement. Two light beams from a laser source are focussed on a transparent pipe containing moving fluid thus setting up an interference pattern of spatial frequency F. Light which is scattered by small particles contained in the moving fluid is detected by a photomultiplier and provides a signal of frequency $F + \Delta F$ where the Doppler frequency shift ΔF is proportional to the speed of particles and hence the fluid flow.

A demonstration of a commercially available laser Doppler anemometer was arranged. De-ionised water was passed through a 10 micron filter and then through a glass tube to provide a transparent point of measurement (see Fig 23). It was found that there were insufficient particles in the water stream to produce a meaningful flow profile, when the flow was manually turned on and off. The accurate measurement of 50 ms pulses of hydrazine were beyond the scope of this otherwise very useful apparatus because of the degree of filtering needed in the fuel for operation with EHTs.

There is an alternative system employing lasers to measure flow velocity called a Ring Laser Flowmeter[4]. This system may with development provide an

alternative optical method with better performance for this application. It uses the Fresnel dragging coefficient concerned with the velocity change of light travelling through a transparent medium. (This states that $\Delta V_e = V_m(n^2 - 1)/n^2$ where V_m is the velocity of the moving medium, n is the index of refraction, ΔV_e is the velocity change of the light and $(n^2 - 1)/n^2$ is called the Fresnel dragging coefficient.) Laser beams are made to traverse both clockwise and anti-clockwise around an optical path passing through the moving liquid (see Fig 24) producing a beat frequency. The beat frequency is altered by the velocity of the fluid, this velocity aiding the light velocity in one direction and subtracting from it in the opposite direction. By electronic processing of this beat frequency a measure of the flow can be obtained.

4.5 Capillary tube flowmeter

The original attempt to measure flow by the test site staff employed a capillary tube flowmeter and as such has been the only meter tried with hydrazine. It consisted of measuring the differential pressure across a 10cm length of 0.25mm bore tube placed just before the electromagnetic fluid control valve. The pressure was measured with an SE 42/150psi TD transducer containing its own oscillator-demodulator unit.

A typical flow output is shown in Fig 25 traced from a UV oscillograph recording of an EHT firing. During this pulse no appreciable back pressure modulation affected the flow. As a result this waveform in essence was obtained in a similar manner to the orifice flowmeter experiments described in section 2.5.

No by-pass valve was connected across the capillary tube to assist in evacuation of the system so there may have been more residual gas to affect the response. However as the differential pressure is proportional to the flow through the tube (as opposed to the square of flow in an orifice) the rate at which the gas downstream of the tube equalises the supply pressure will be much slower than with the orifice meter.

5 CONCLUSIONS

Two liquid meters developed experimentally to measure small hydrazine propellant expulsions have been described. De-ionised water was used as a representative flow substitute for their development, with minimum liquid pulses of <5 mg expelled in 50 ms every 450 ms. Because of changes in the EHT development programme no opportunity to connect the meters into an EHT test site rig has arisen. The first meter adopted the principle of the well established orifice flowmeter. From the results obtained there appears to be no fundamental

reason why the steady flow calibration cannot be transferred to the integrated output signal to acceptably assess the total amount of fuel used per EHT pulse. Accuracies within ±2% for the inconstant fluid accelerations through the orifice were easily achieved for liquid expulsions as specified above. As regards the flow signal being a facsimile of the flow variation profile through the EHT injector tube, this will largely depend on the mass of residual gas in the intervening volume. A rise time of 40 ms was achieved, just after evacuation with a rotary pump of the prototype system.

Meticulous care will have to be taken with cleanliness and filtering of the system and attention paid to the joints of dissimilar metals to prevent residue arising from electrolytic reaction partially blocking the very small area orifice.

The orifice meter developed lends itself for ready adaptation to various flow ranges by changing the transducer range and/or changing the orifice plate. This makes it a very versatile instrument being merely a series element in the plumbing of any small fast varying flow system.

The second meter (the Liquid Expulsion Meter) showed very good linearity. Over its complete volumetric displacement range of 50 mm^3 the V/mg calibration had a maximum error of ±0.7% for a supply pressure of 965 kN/m^2. After the mass of gas in the system had been simply determined pulses as described above could be resolved to within 1% without difficulty. This instrument is more accurate for resolving the mass of very small liquid expulsions but unlike the orifice meter has not the advantage of measuring continuous flow.

The expulsion range could be altered by various size bellows and if larger vertical displacements were envisaged an inductive technique similar to that in section 4.2 could be used to replace the capacitive transducer.

The other five techniques described although limited either in response or resolution for the EHT application, with development may be of use for other fluid measuring problems.

Appendix A

RESPONSE OF IDEALISED ORIFICE FLOWMETER

With reference to Fig 1 when the flow control valve is opened the gas volume V will cause a delay in the downstream pressure P_2 reaching equilibrium. This is due to the gas, originally at the supply pressure P_1, expanding as the pressure P_2 reduces when the valve is opened. Assuming the gas undergoes isothermal expansion P_2V equals B, a constant. The flow through the orifice dm_1/dt is expressed by $\sqrt{P_1 - P_2}/R_1$ and through the injector tube dm_2/dt by P_2/R_2 (Poiseuille's formula) where both R_1 and R_2 are constants representing collectively the dimensions of the orifice and tube.

At the instant the valve opens the gas volume V is increased by the volumetric flow through the injector and reduced by the flow through the orifice:-

$$V + \frac{1}{R_2}\int P_2 dt - \frac{1}{R_1}\int \sqrt{P_1 - P_2}\, dt = \frac{B}{P_2} . \tag{10}$$

Differentiating with respect to t,

$$\frac{P_2}{R_2} - \frac{\sqrt{P_1 - P_2}}{R_1} = -\frac{B}{P_2^2}\frac{dP_2}{dt} , \tag{11}$$

therefore

$$\frac{dP_2}{dt} - \frac{P_2^2\sqrt{P_1 - P_2}}{BR_1} + \frac{P_2^3}{BR_2} = 0 . \tag{12}$$

When the valve closes the initially increased gas volume V_2 starts to decrease, by the volumetric flow through the orifice, back to V :-

$$V_2 - \frac{1}{R_1}\int \sqrt{P_1 - P_2}\, dt = \frac{B}{P_2} \tag{13}$$

therefore

$$\frac{dP_2}{dt} - \frac{P_2^2\sqrt{P_1 - P_2}}{BR_1} = 0 . \tag{14}$$

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Some appropriate values were assigned to the constants in equations (12) and (14) to illustrate the reduced response of the orifice flow meter pressure signal, to the flow through the injector tube. With reference to section 2.1 the steady supply pressure P_1 was 410 kN/m^2 and for a flow rate of 100 mg/s through the orifice a pressure drop of 21 kN/m^2 was assumed. The initial volume of gas was 126 mm^3. Therefore:-

$$V = 126 \text{ mm}^3$$
$$B = 0.052 \quad \textit{ie} \ (P_1V = B)$$
$$R_2 = 389 \times 10^{-4}$$
$$R_1 = 4.58 \times 10^{-4} \ .$$

Equations (12) and (14) were solved by iteration in 1 ms steps, for a valve on time of 12 ms. The resulting flows through the orifice meter and injector tube are illustrated in Fig 2.

Appendix B

DETERMINATION OF GAS VOLUME IN LEM

(see section 3.4)

If the mass of gas in the system is appreciable there will be a difference between the bellows and liquid volume displacements. This is caused by the gas expanding when the bellows stiffness produces a pressure drop with displacment. Referring to Fig 15

$$V_g \frac{P_1}{P_2} + V_L = V_T \tag{15}$$

$$P_2 = P_1 - \frac{Ks}{A} \tag{16}$$

where P_1 is the nitrogen supply pressure
V_L is the liquid volume downstream of valve 1
V_g is the gas volume downstream of valve 1
V_T is the total volume downstream of valve 1
K is the bellows spring rate
A is the bellows effective area
s is the bellows displacement
P_2 is the fluid pressure .

Combining (15) and (16)

$$V_L = V_T - \frac{V_g}{1 - \frac{Ks}{AP_1}} \ . \tag{17}$$

Equating changes in volume

$$\delta V_L = As - V_g \left\{ 1 - \frac{1}{1 - \frac{Ks}{AP_1}} \right\} \ . \tag{18}$$

If $\frac{Ks}{AP_1} \ll 1$ as will be the case for most EHT work

then

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$$\delta V_L \triangleq As - V_g \left\{1 - \left(1 + \frac{Ks}{AP_1}\right)\right\} \tag{19}$$

therefore

$$\delta V_L \triangleq As \left\{1 - \frac{V_g k}{A^2 P_1}\right\} . \tag{20}$$

The liquid volume expelled will be greater than the bellows displacement by an error of approximately

$$\frac{100 V_g K}{A^2 P_1} \% .$$

The mass of gas can be determined by measuring the compression of the bellows, with both valves 1 and 2 closed when the nitrogen supply pressure is increased from P_1 to some pressure P_3 . Assuming the gas undergoes isothermal compression

$$P_1 V_{g_1} = B = P_2 V_{g_2} \tag{21}$$

where B is a constant and P_1 and P_2 are fluid pressures.

From equation (16)

$$P_2 = P_3 - \frac{Ks}{A} . \tag{22}$$

As for all practical reasons only the gas can change volume with both valves shut

$$V_{g_2} = V_{g_1} - As . \tag{23}$$

Substitute (22) and (23) in (21)

$$\left(P_3 - \frac{Ks}{A}\right)\left(V_{g_1} - As\right) = P_1 V_{g_1} \tag{24}$$

therefore

$$V_{g_1} = \frac{As}{1 - \dfrac{P_1}{P_3 - \dfrac{Ks}{A}}} . \tag{25}$$

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3	F.M. Clark	*Insulating materials for design and engineering practice.* p 91, London, John Wiley & Sons (1962)
4	R.N. Blazey J.R. Schneider	Characteristics of a high response laser flow-meter. In *Advances in instrumentation*, Vol 23, Part 1, p 869, Pittsburgh. Instrument society of America (1968)

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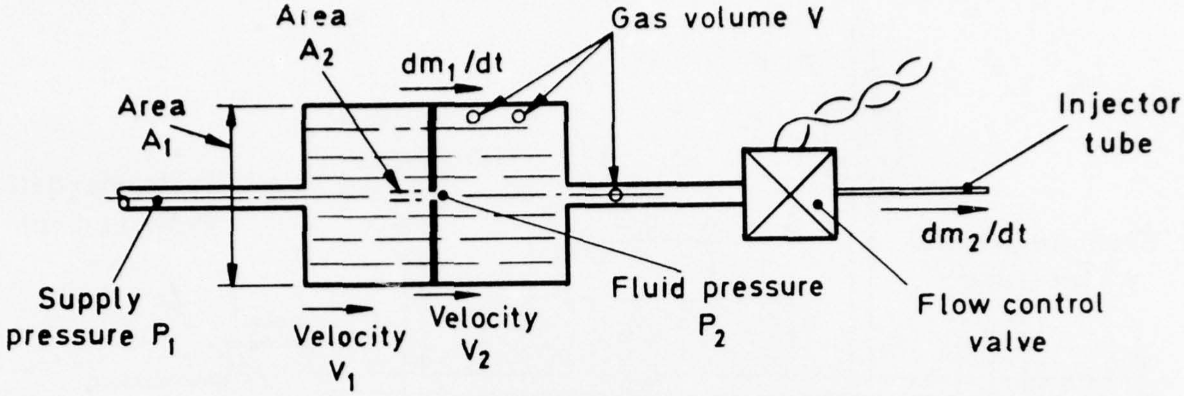

Fig 1 Hypothetical orifice flowmeter

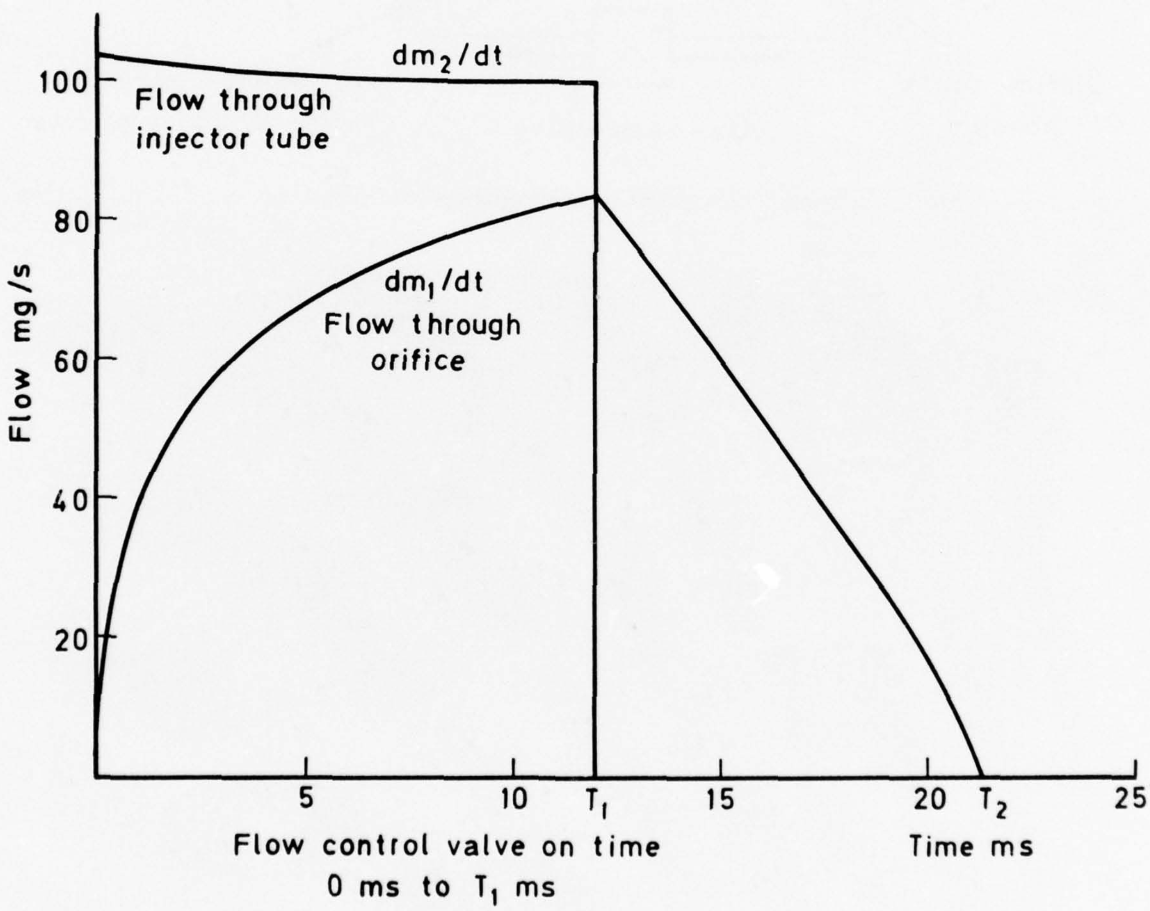

Fig 2 Effects of gas on response of idealised orifice flowmeter

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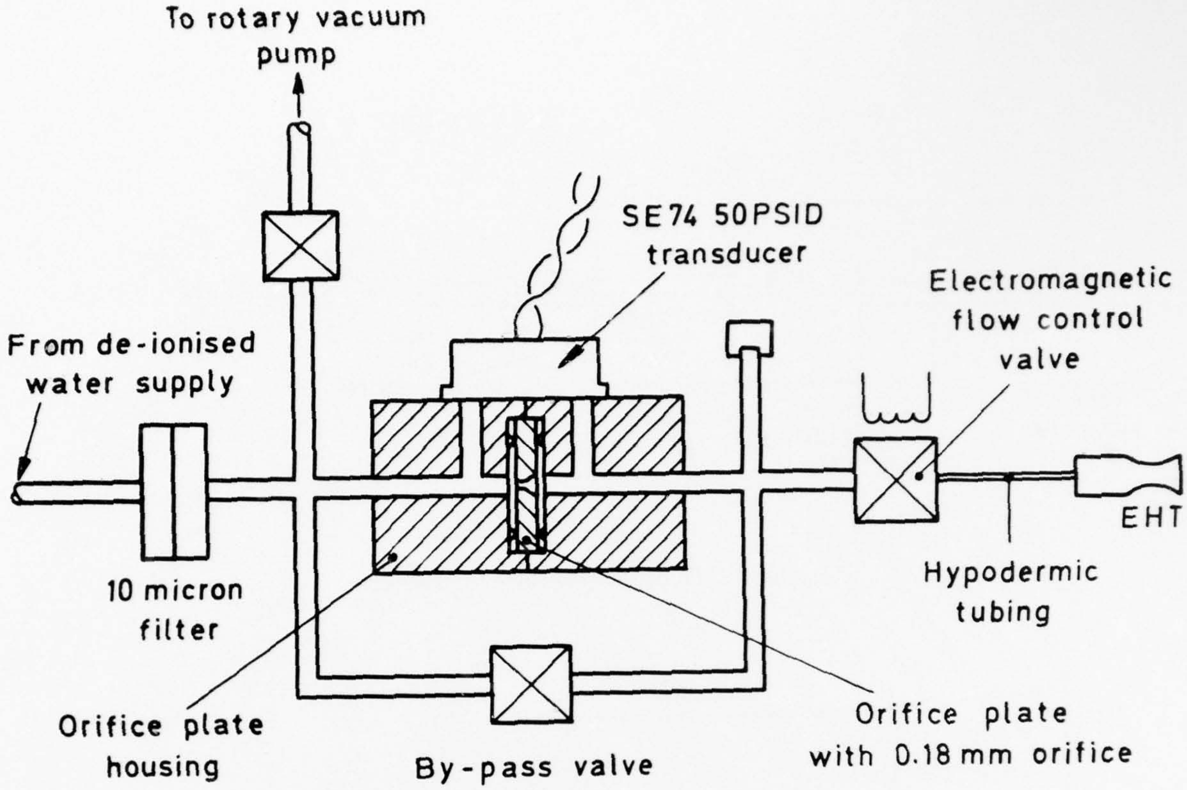


Fig 3 Schematic diagram of experimental orifice flowmeter

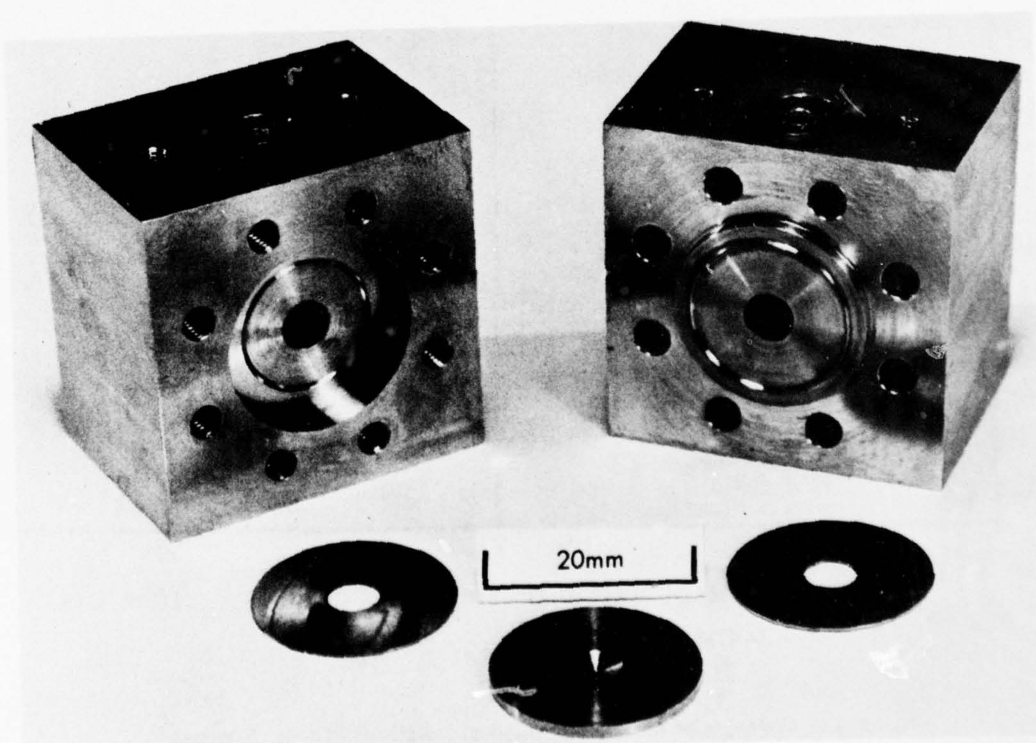


Fig 4 Dismantled orifice plate housing

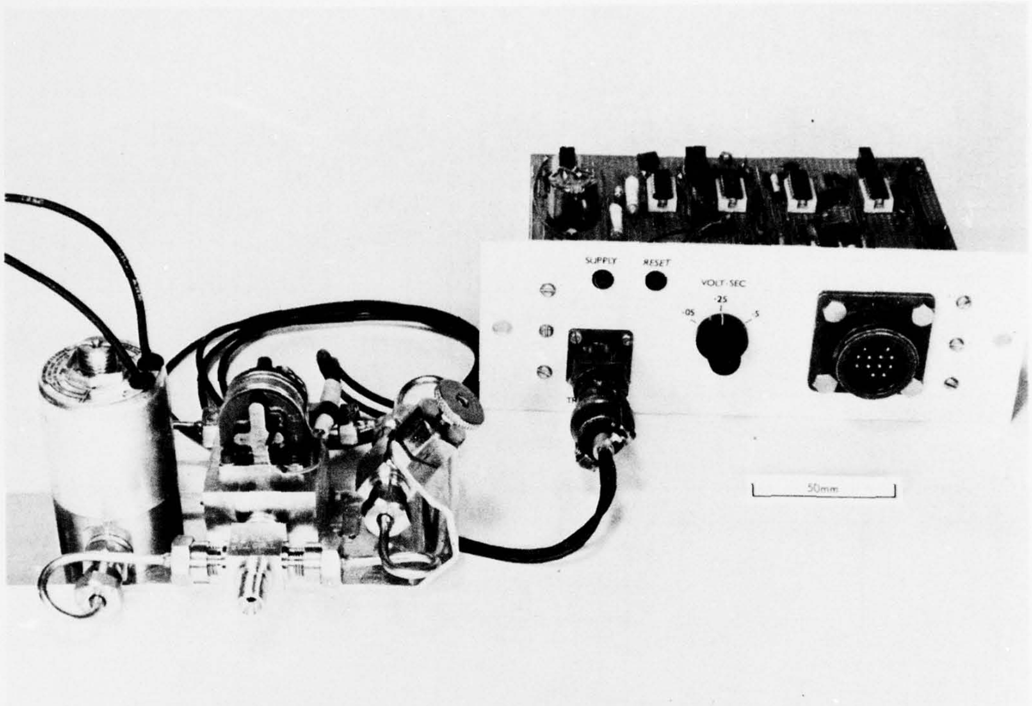


Fig 5 Prototype orifice flowmeter assembly

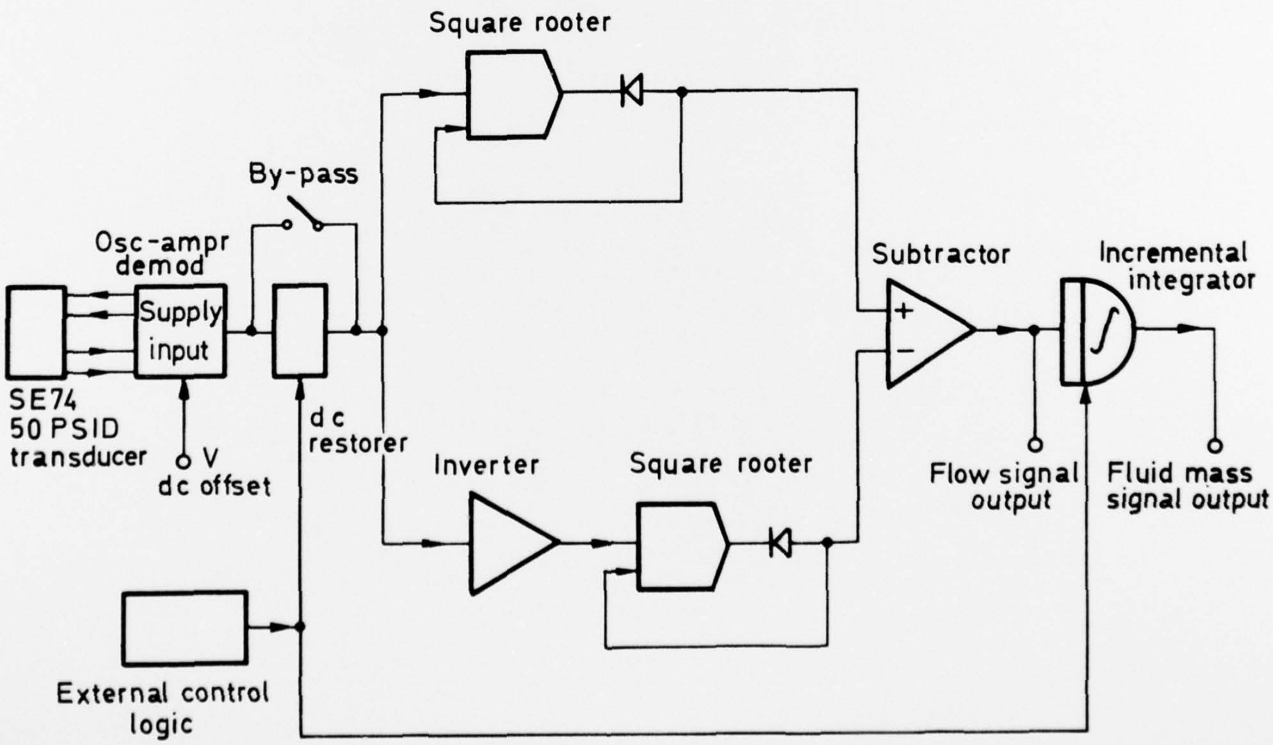
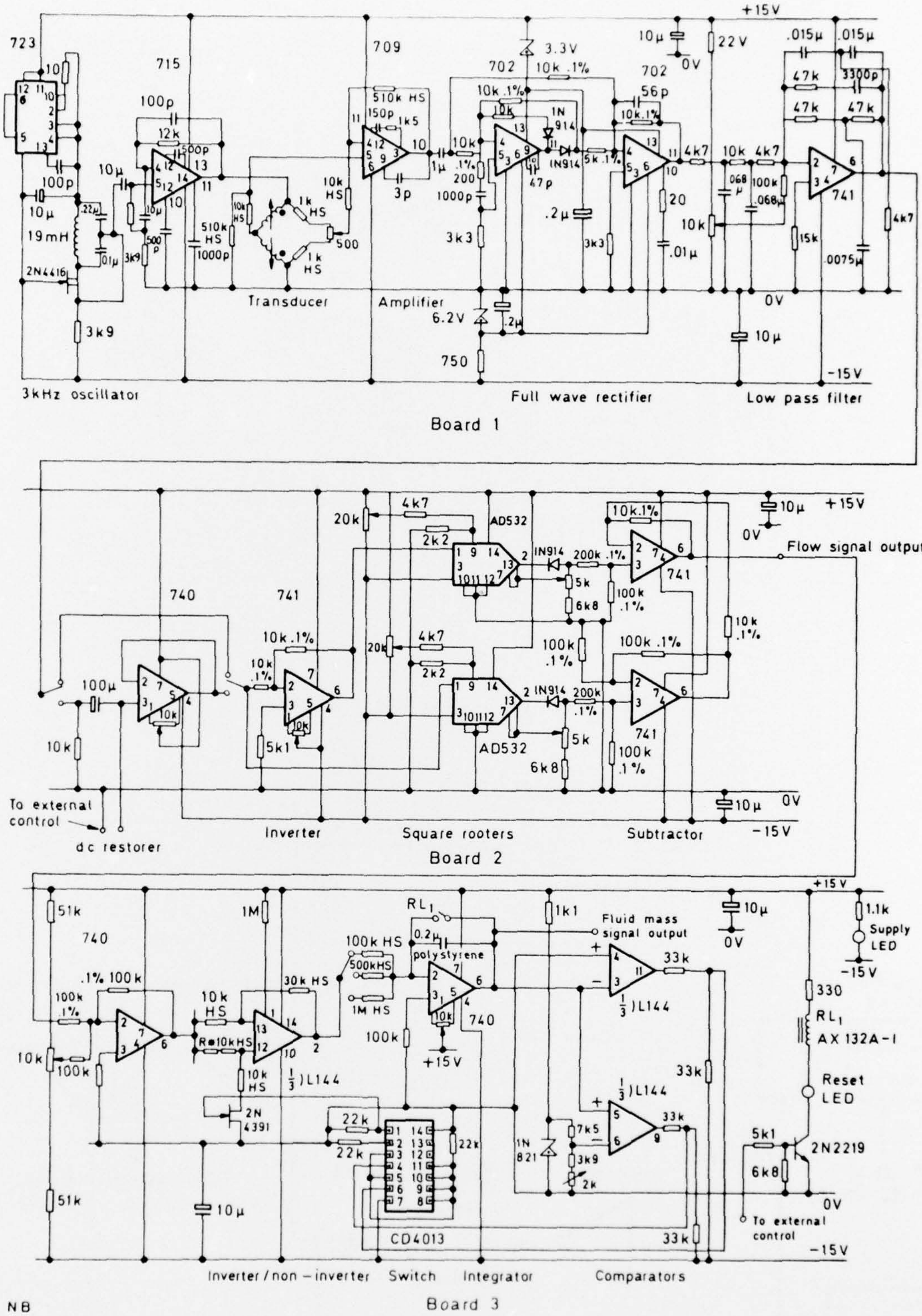


Fig 6 Schematic diagram of orifice flowmeter electronics

Fig 7



NB
R✱ adjusted to equal
2N4391 rds on

Fig 7 Circuit diagram of orifice flowmeter

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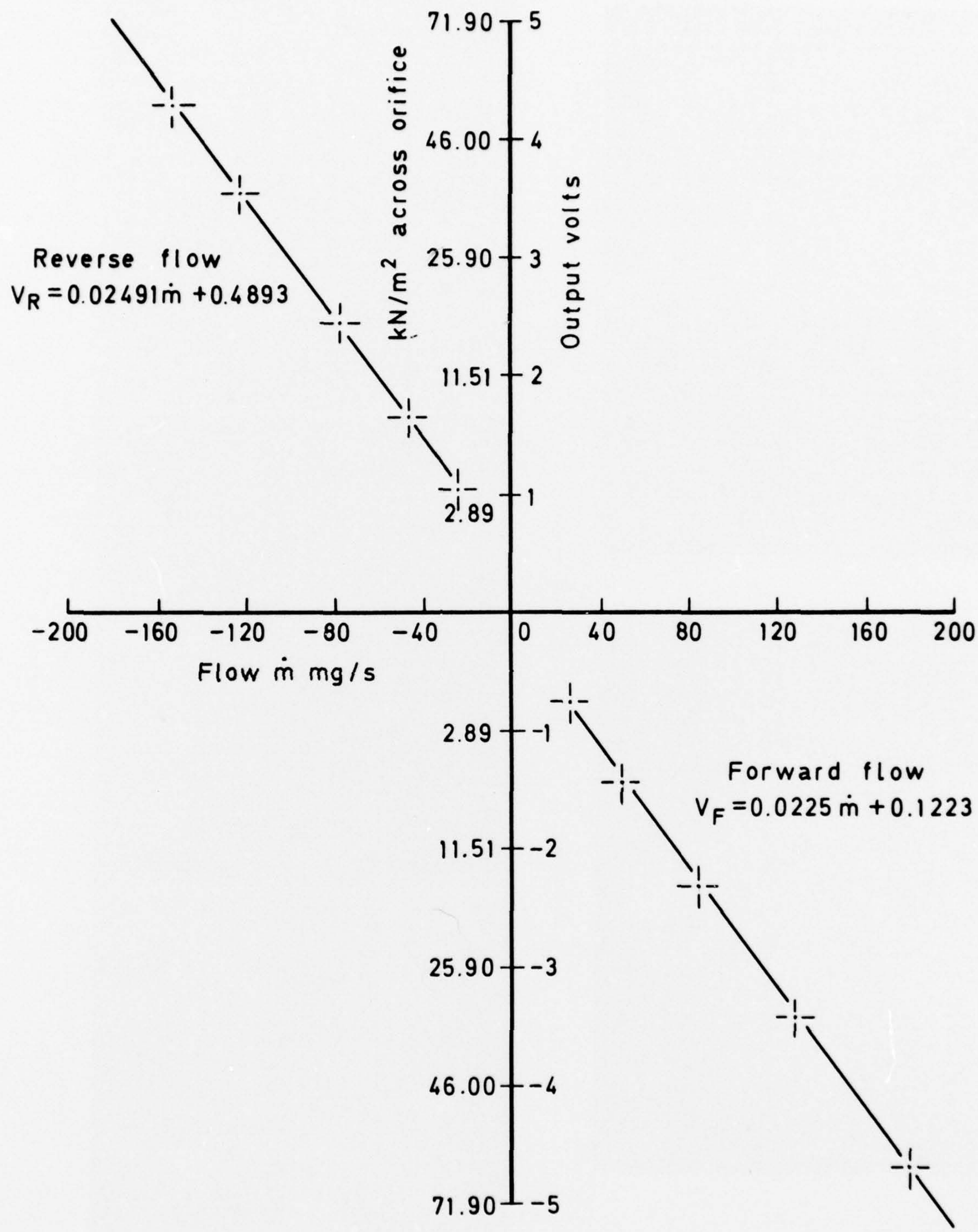

Fig 8 Steady flow calibration of prototype orifice meter

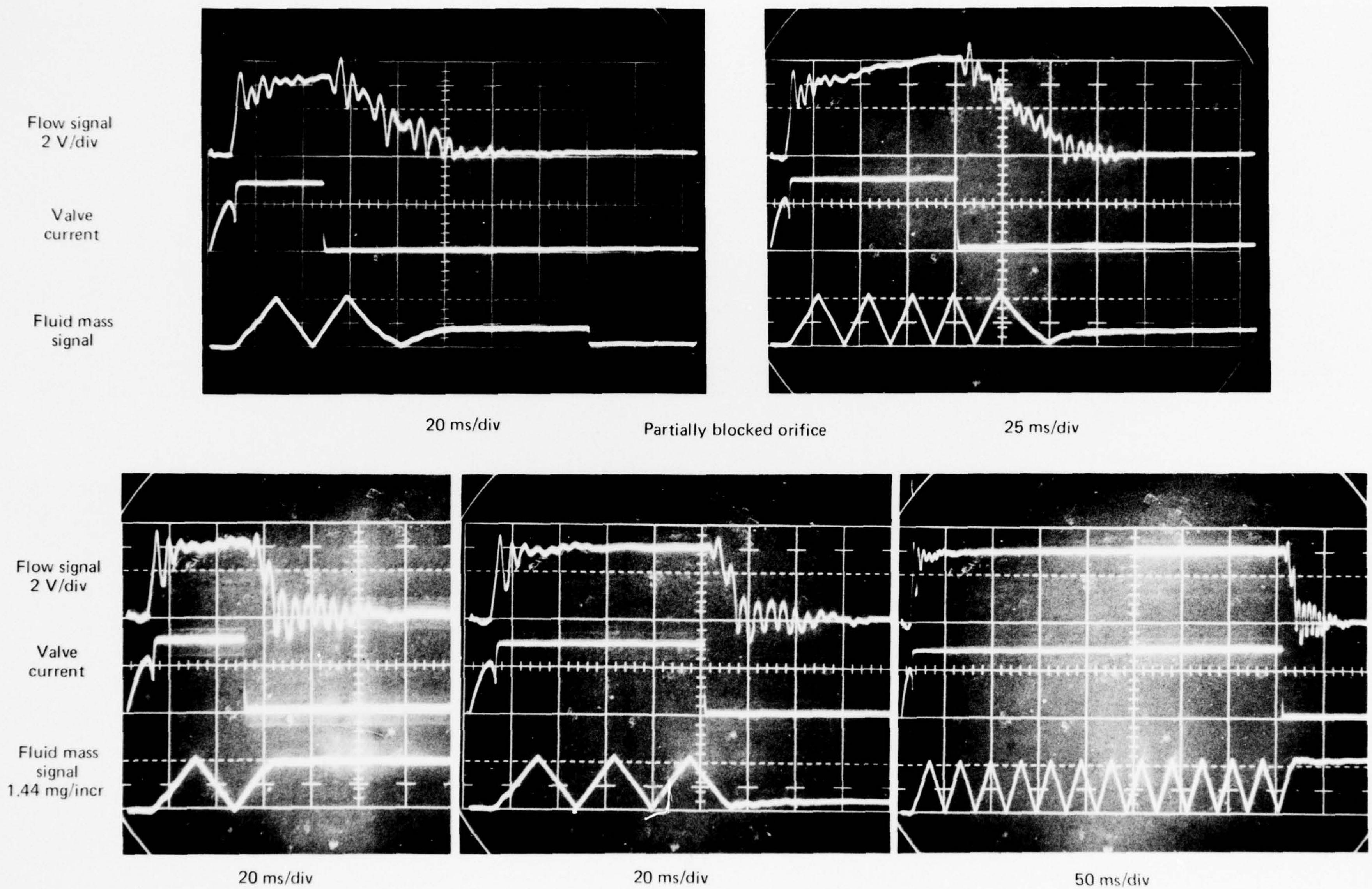

Fig 9 Pulsing flows through orifice meter

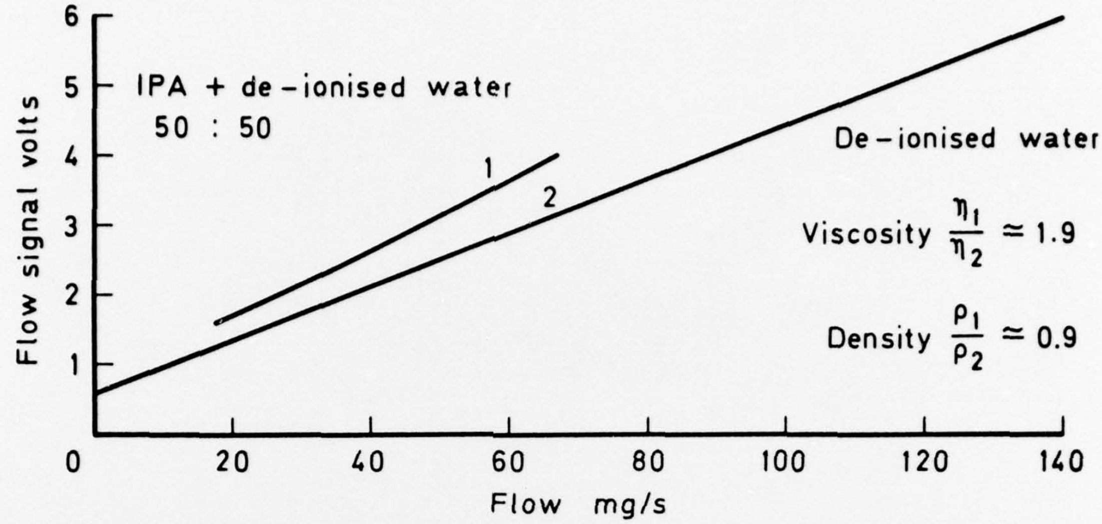

Fig 10 Viscosity effects

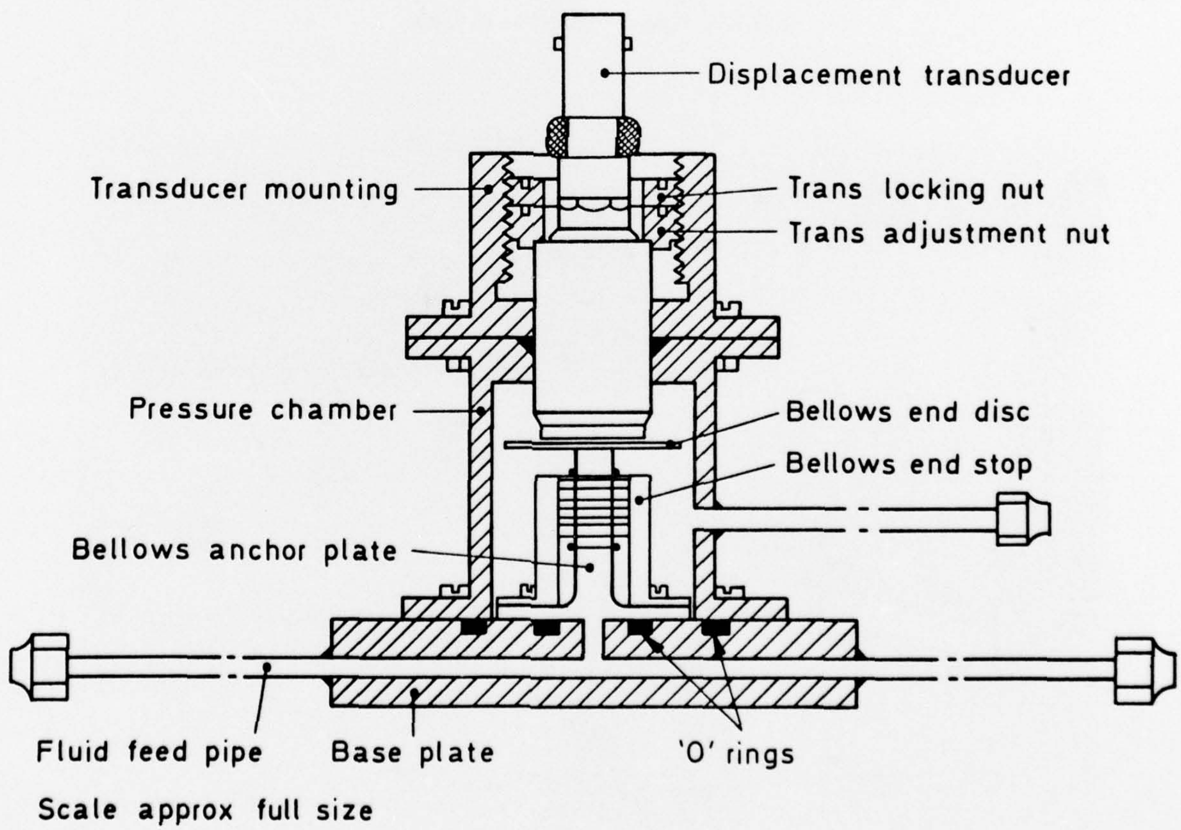

Fig 11 Sectional view of LEM

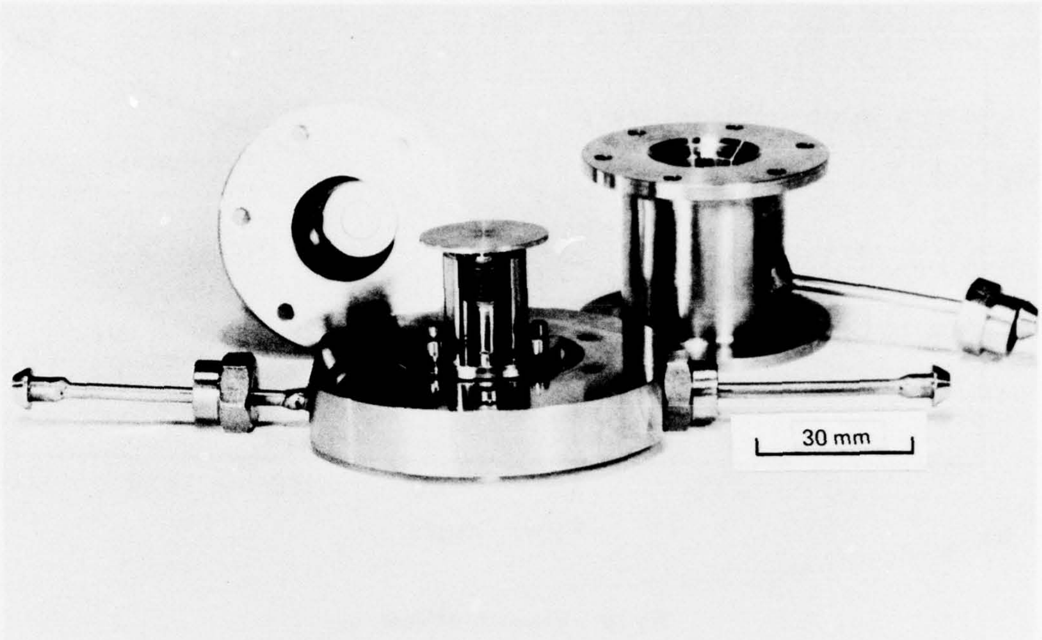

Fig 12 Dismantled view of LEM

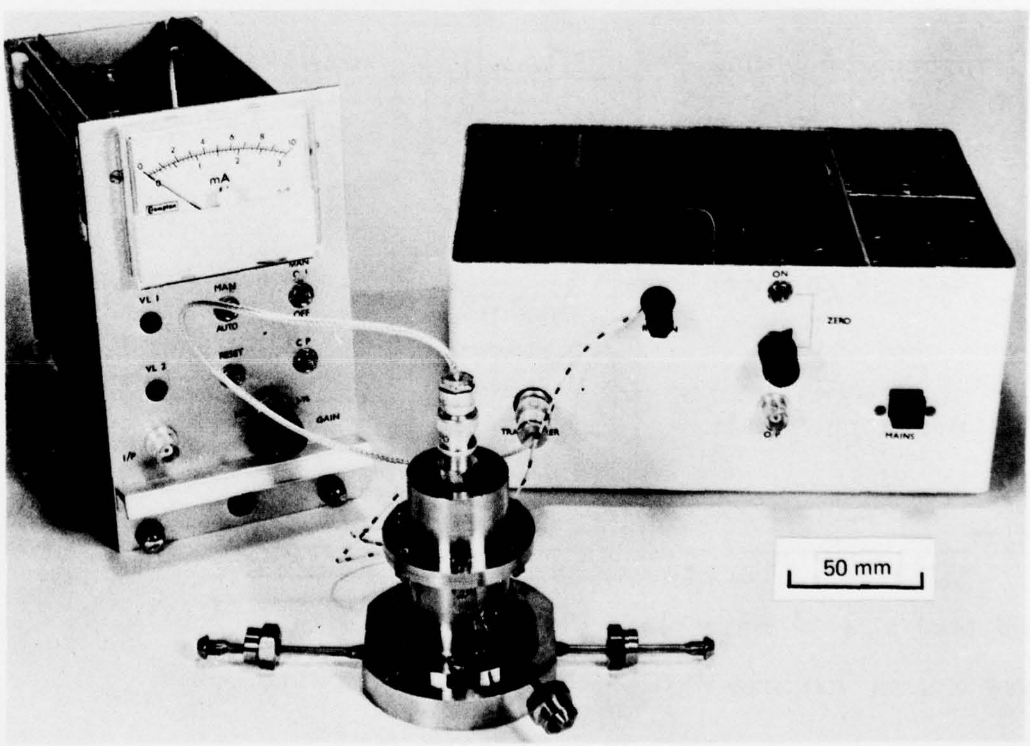

Fig 13 LEM assembly and electronics

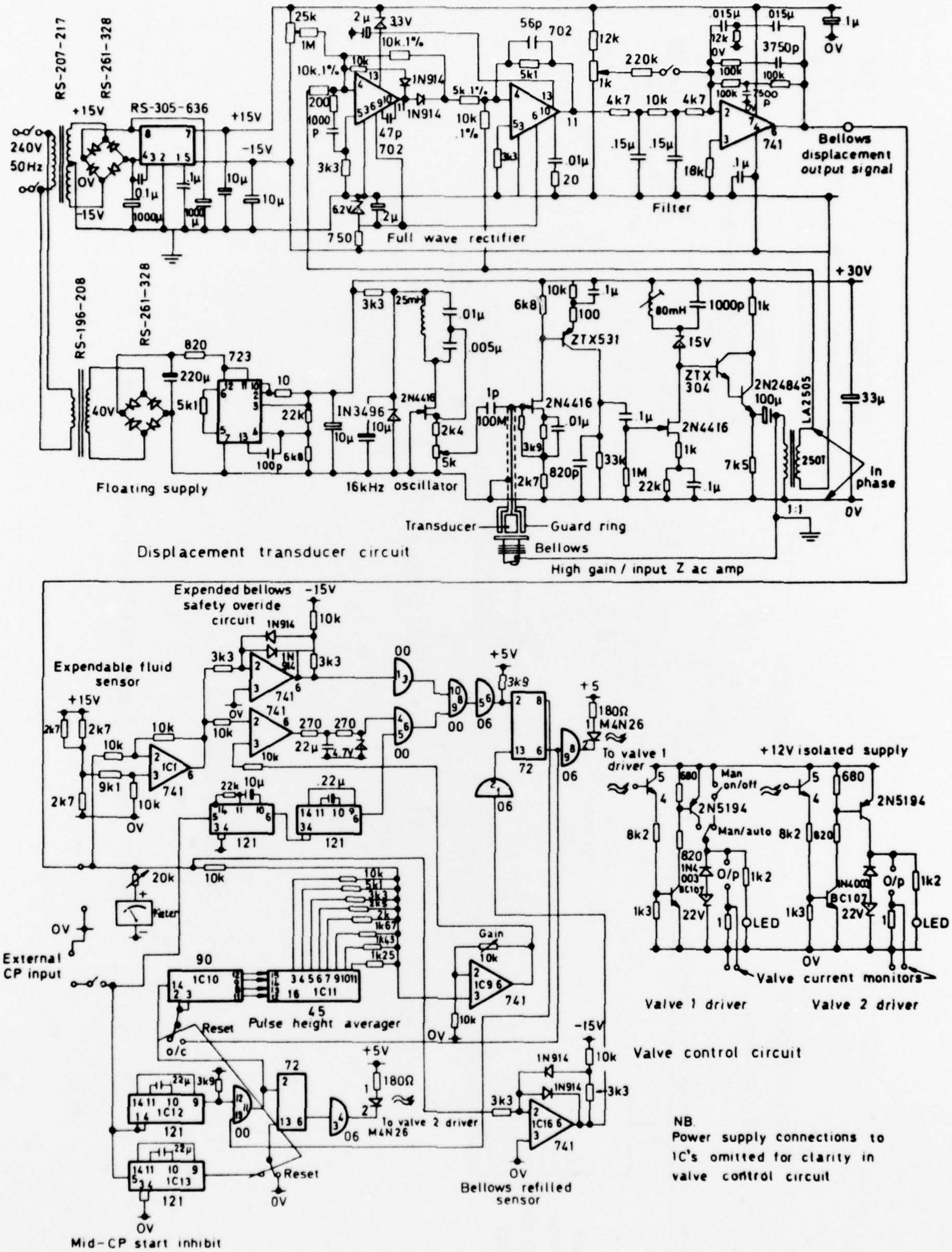

Fig 14 Displacement transducer and valve control circuit

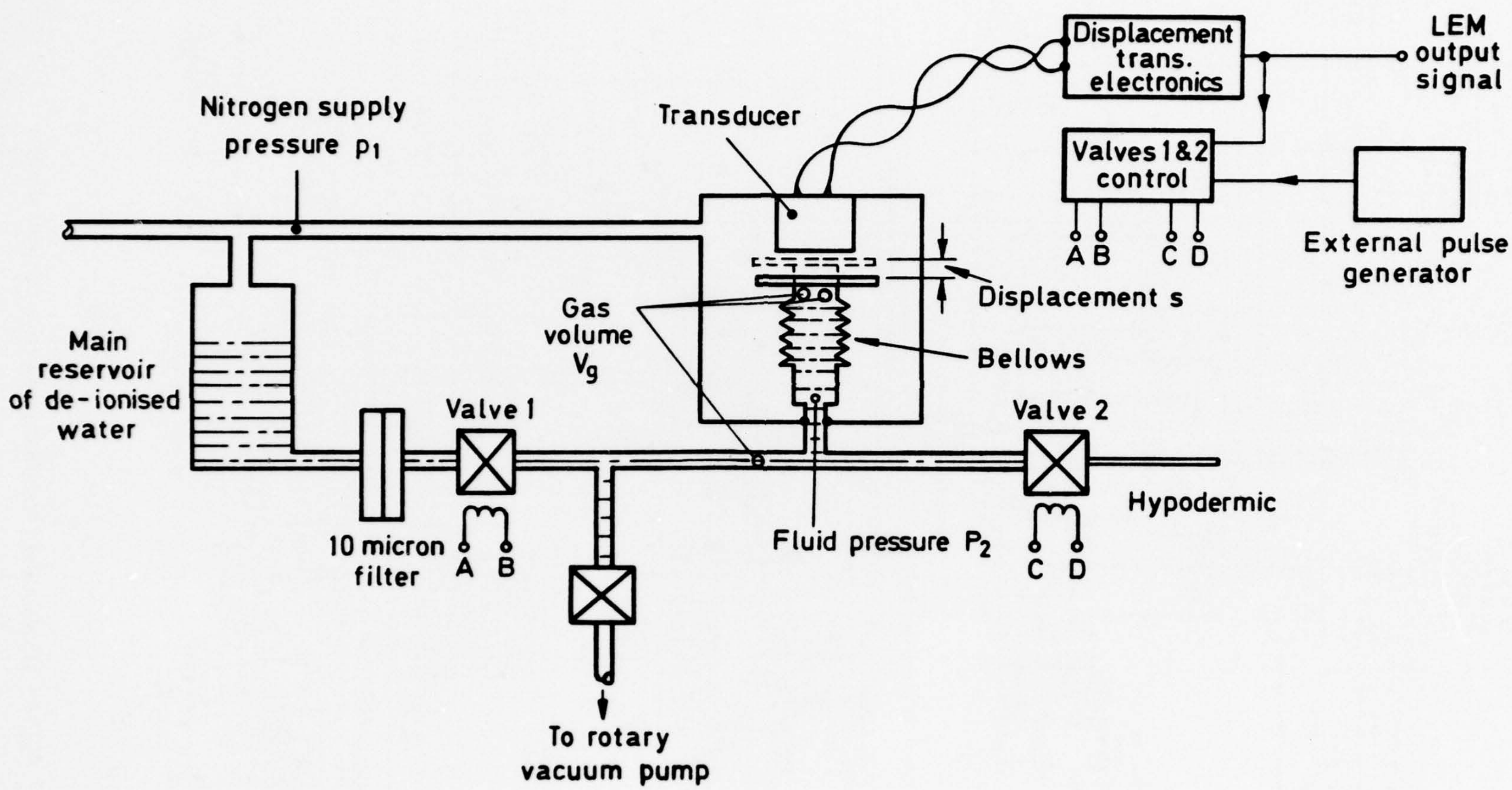

Fig 15 Schematic diagram of LEM calibration apparatus

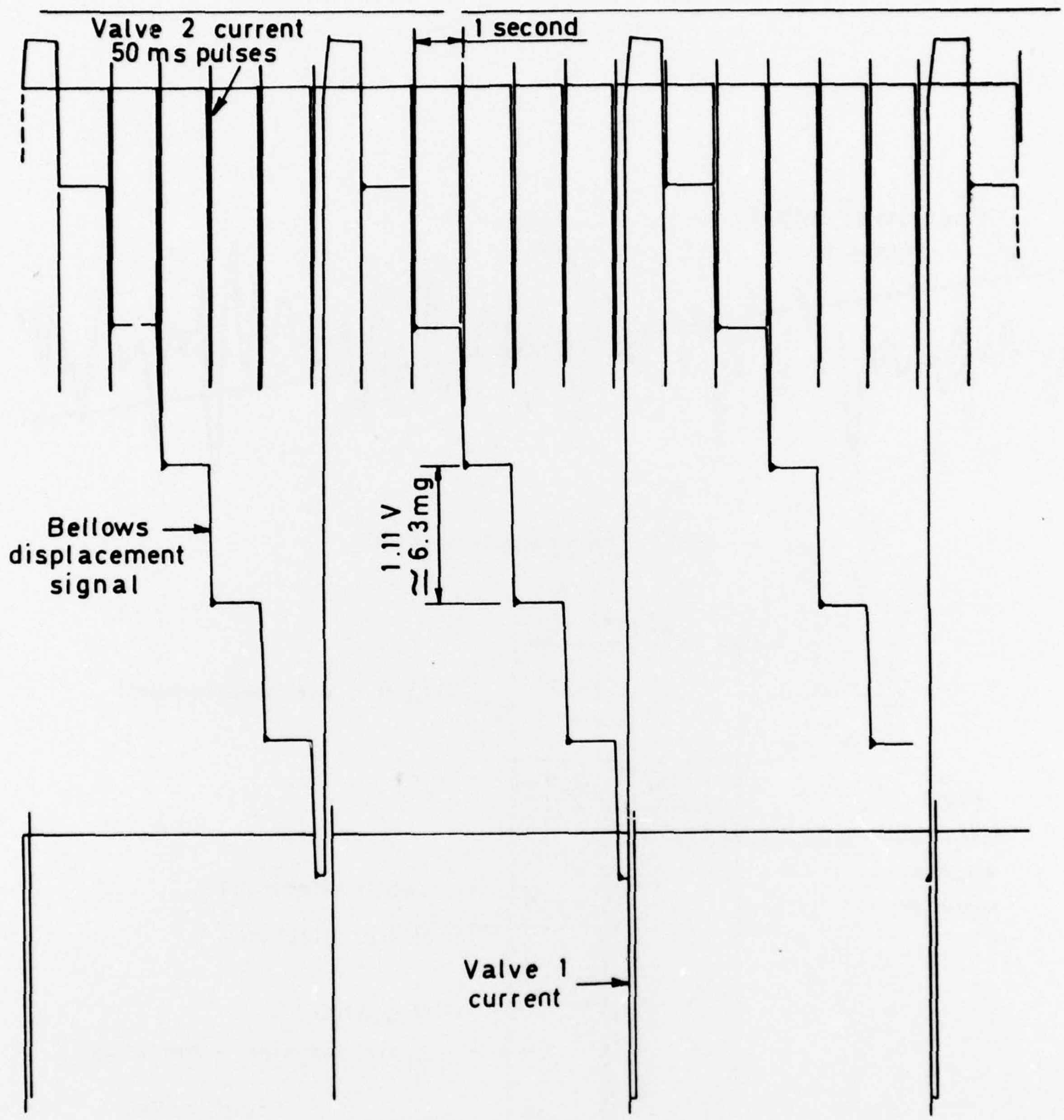

Fig 16 Sequence of LEM pulses

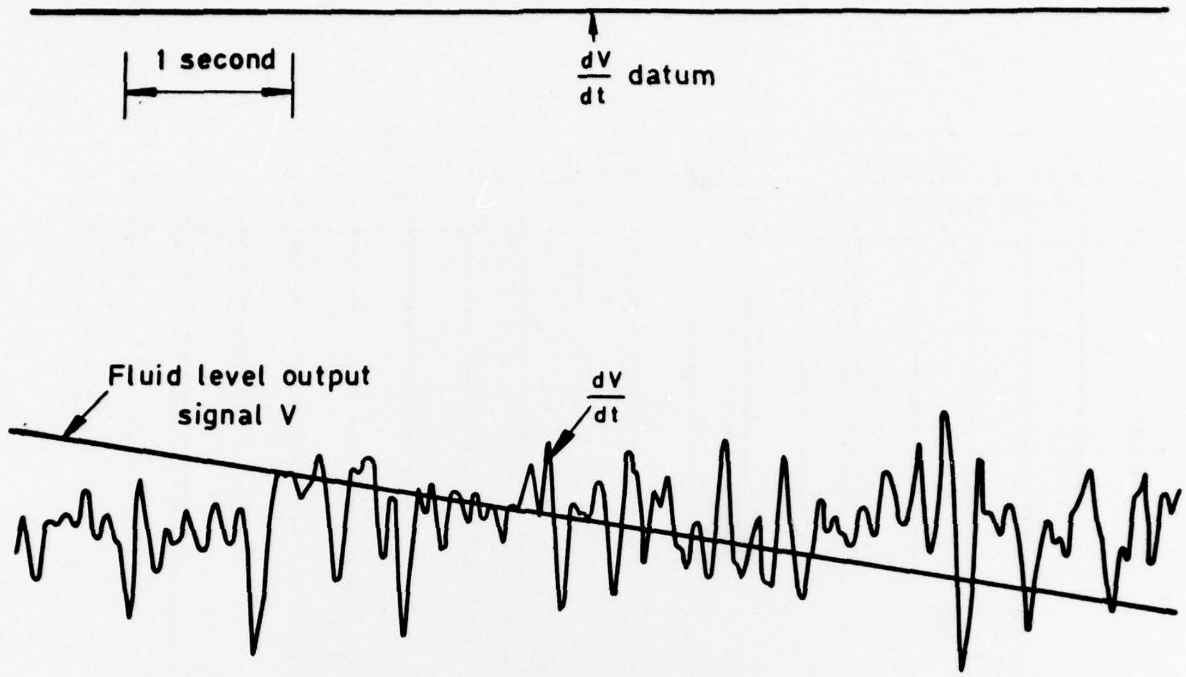

Fig 17 Output signal from CLS

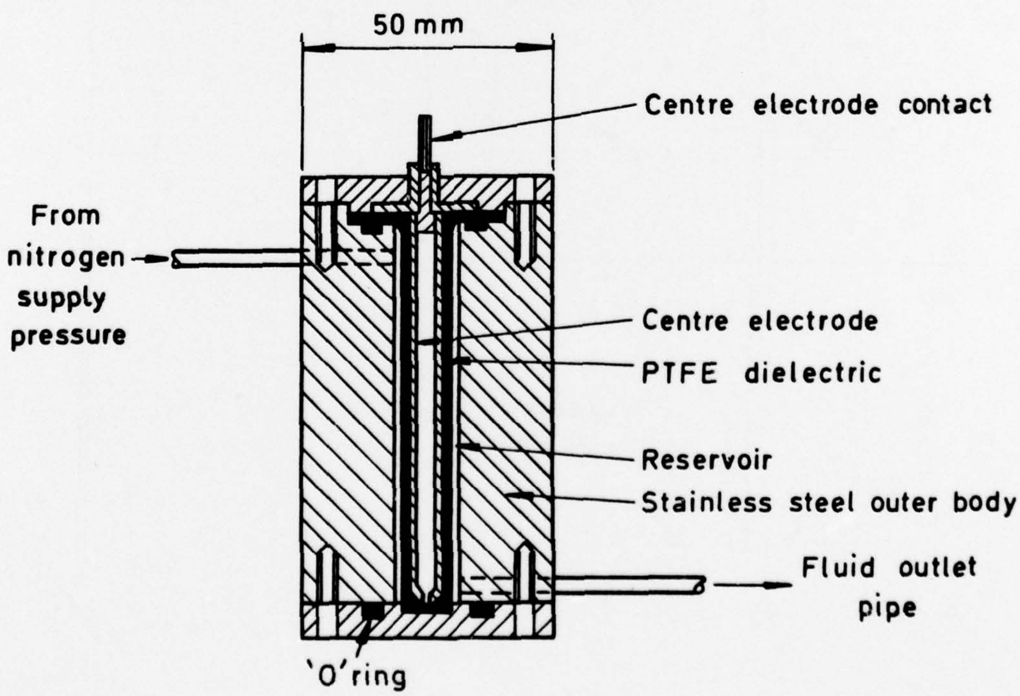

Fig 18 Capacitance level sensor (CLS)

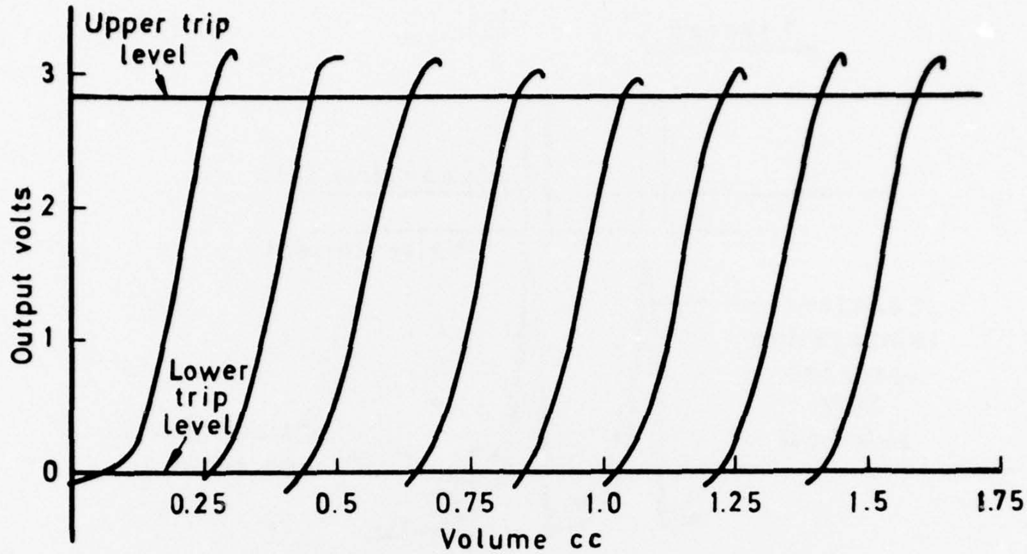

Fig 19 IPLS output calibration

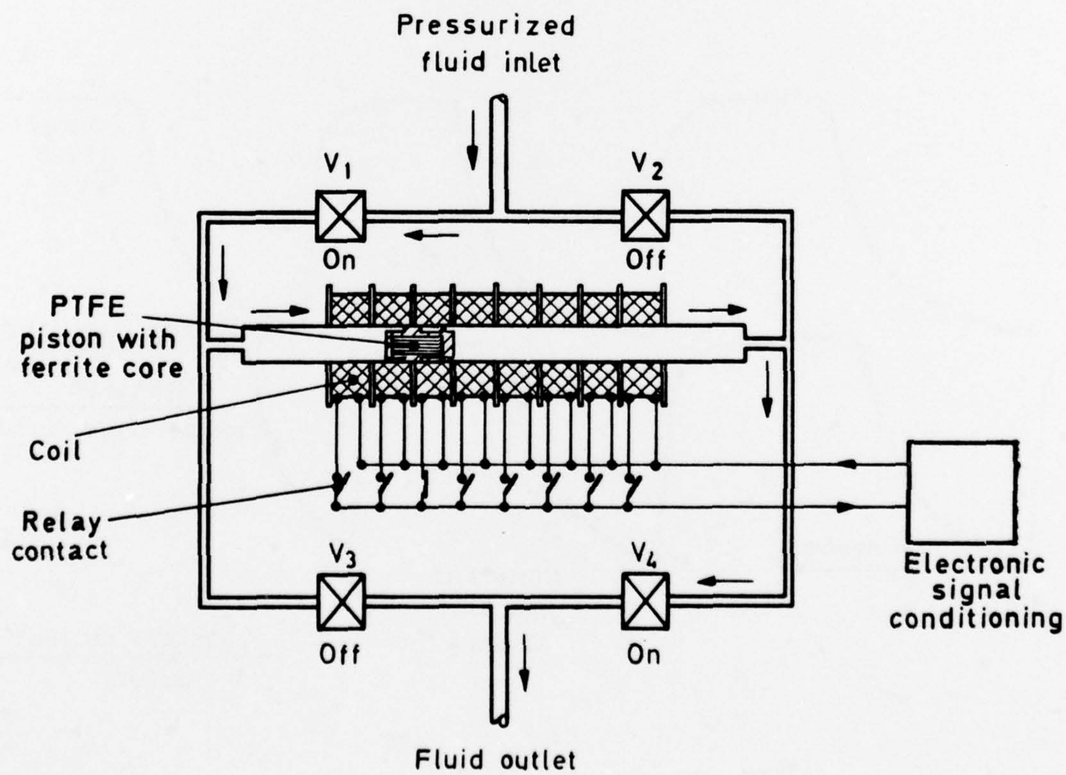

Fig 20 Inductive piston level sensor (IPLS)

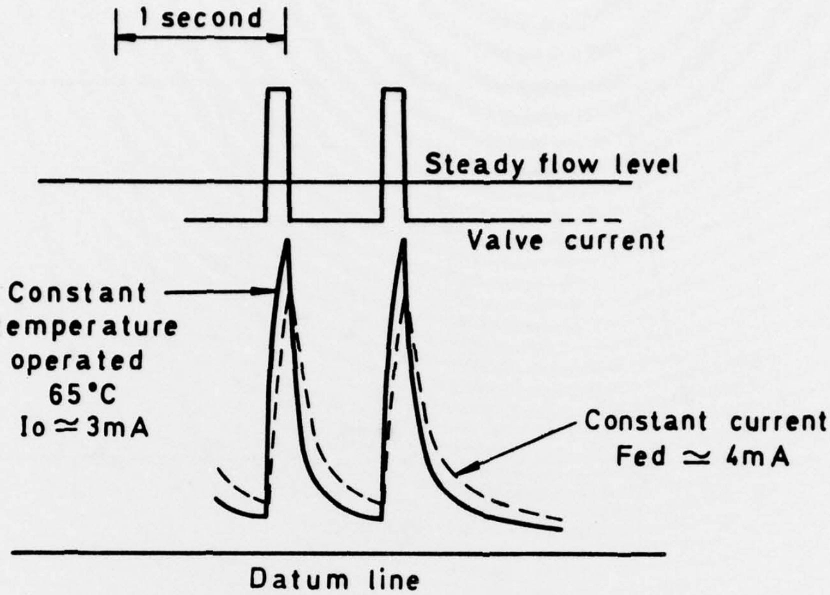

Fig 21 Constant current : constant temperature response of thermistor

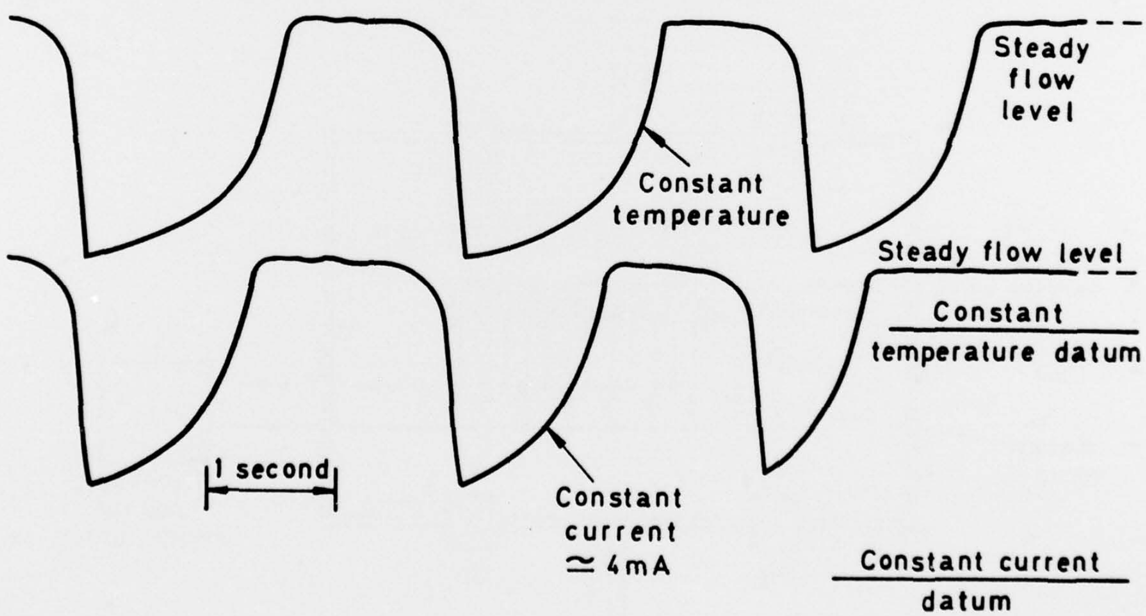

Fig 22 Response of thermistor to liquid flow

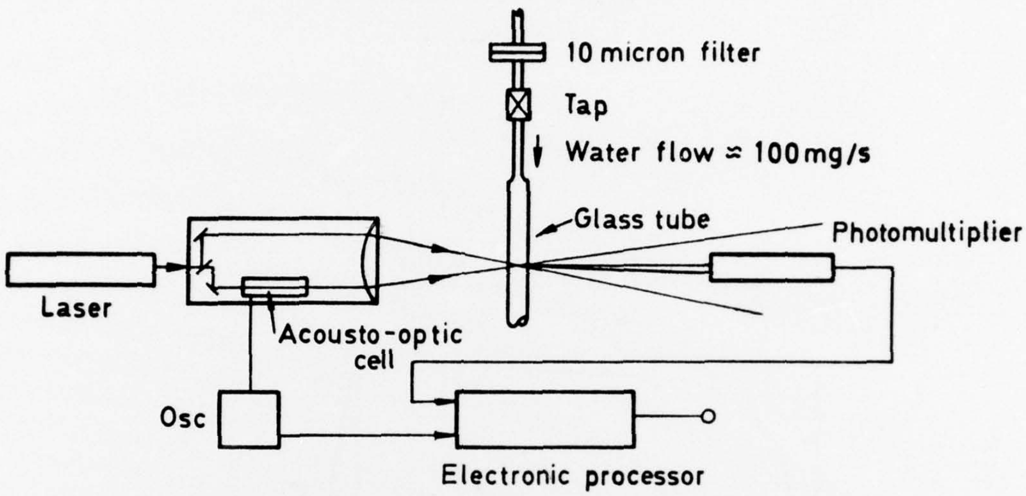

Fig 23 Laser Doppler anemometer

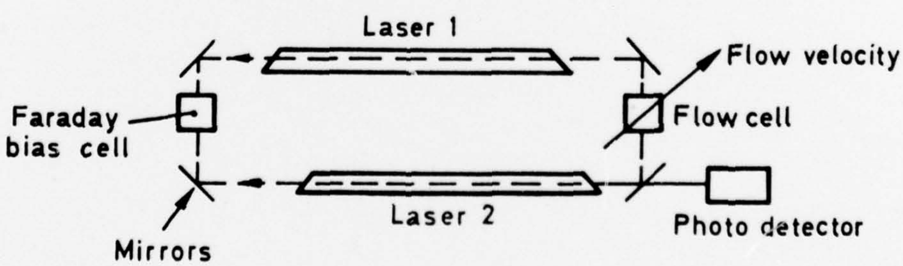

Fig 24 Ring laser flowmeter principle

Fig 25

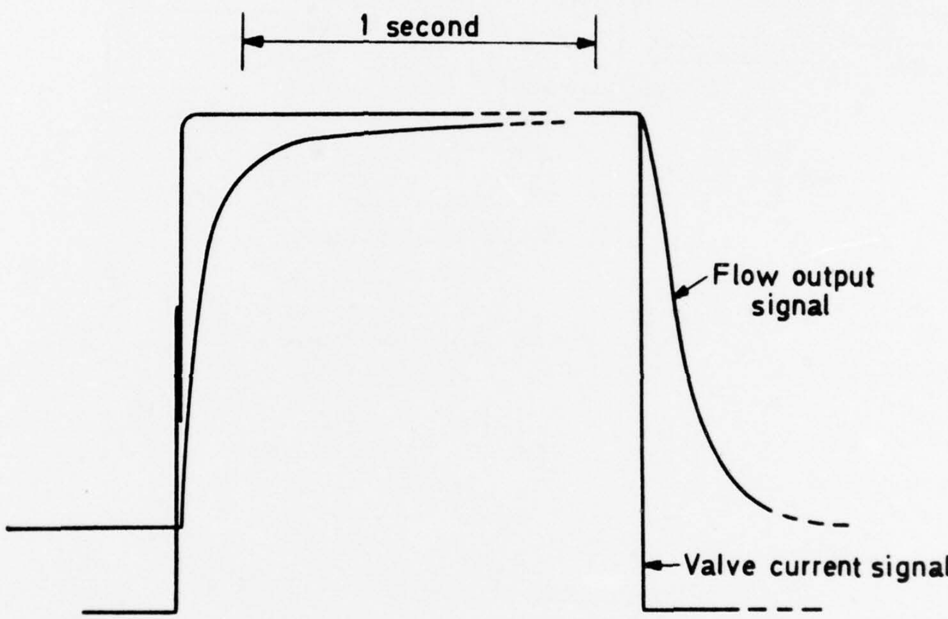

Fig 25 Capillary tube flow meter output signal

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